



Surge Irrigation: Advancements, Challenges, and Prospects in Agricultural Water Management

Gabriel Angelo L. Rubia

Bataan Peninsula State University
Capitol Compound, Tenejero, City of Balanga, Bataan 2100, Philippines
<https://orcid.org/0009-0004-2930-2579>
galrubia@bpsu.edu.ph

Mohamad Safaat

Universitas Bina Mandiri Gorontalo
mohamad.safaat@ubmg.ac.id

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Abstract

Surge irrigation has emerged as an innovative solution to improve water management in agriculture, addressing critical limitations of conventional irrigation methods. This technique involves the intermittent application of water through controlled, cyclic flows, resulting in optimized water distribution and infiltration efficiency. Recent studies have shown that surge irrigation can achieve water savings of up to 40% and crop yield improvements ranging from 15% to 30%, particularly in row crops such as maize, wheat, and cotton, compared to traditional furrow irrigation. These improvements are facilitated by reducing deep percolation losses, enhancing soil moisture uniformity, and minimizing erosion. This review comprehensively analyzes surge irrigation's principles, benefits, challenges, and advancements. Recent technological developments, including automated surge controllers, precision timing systems, and integration with smart sensors for real-time monitoring, have significantly enhanced the efficiency and adaptability of surge irrigation. Despite its benefits, challenges remain, including high initial investment costs, variability in soil types, and the need for technical expertise. The adoption of surge irrigation is further limited in resource-constrained areas, where infrastructure and training support are lacking. This article also highlights the potential of surge irrigation to contribute to Sustainable Development Goals (SDG) 6 (Clean Water and Sanitation) and SDG 2 (Zero Hunger) by promoting sustainable water use and increasing agricultural productivity. Scaling up this technology requires collaborative efforts involving policymakers, researchers, and farmers, as well as advancements in automation, AI integration, and remote sensing. By addressing key barriers and harnessing technological innovations, surge irrigation can play a transformative role in building water-resilient agricultural systems. It holds immense promise for ensuring food security, conserving water resources, and supporting sustainable development, particularly in water-stressed and arid regions.

Keywords: Surge irrigation, water management, precision agriculture, automated irrigation, sustainable agriculture, SDG 6, SDG 2, crop yield, water savings, smart irrigation systems

Introduction

Water scarcity has emerged as one of the most critical challenges in global agriculture, threatening food security, economic stability, and sustainable development. Traditional irrigation methods, while widely used, are increasingly inefficient and unsustainable in water-stressed regions. Furrow irrigation, one of the oldest surface irrigation techniques, often suffers from deep percolation losses, uneven water distribution, and excessive soil erosion. Reports indicate that up to 40% of water applied through conventional furrow irrigation is lost due to infiltration and evaporation (Alejo & Espino, 2020). Addressing these inefficiencies requires innovative solutions such as surge irrigation, which optimizes water application through intermittent, controlled flows, enhancing irrigation efficiency and conserving water resources.

Surge irrigation operates on the principle of cyclic water flow—alternating "on" and "off" periods to improve infiltration uniformity and reduce water losses. Early studies have demonstrated that surge irrigation increases water application efficiency by 20-30% compared to continuous flow methods (Yonts et al., 1996). For example, Kaur et al. (2021) reported water savings of 27% to 37% and yield improvements of 12% to 18% for wheat crops under surge irrigation across varying field slopes. This efficiency arises from the reduced infiltration

opportunity time during the alternating cycles, which minimizes water seepage and promotes uniform wetting along furrows.

Globally, the adoption of surge irrigation has shown promising results across diverse agro-climatic conditions. In arid regions like India's Punjab and Haryana, where water scarcity severely impacts agricultural productivity, surge irrigation has been demonstrated to conserve up to 30-40% of irrigation water for maize and sugarcane crops (Mintesinot et al., 2007). Similarly, in semi-arid regions of Australia, trials on cotton fields revealed that surge irrigation reduced infiltration losses by 35% while maintaining high crop yields (Koech et al., 2014). These results highlight the adaptability of surge irrigation to various climates and soil conditions, making it a versatile solution for water-efficient farming.

Surge irrigation offers distinct advantages over other water-saving irrigation technologies, such as drip irrigation and traditional continuous flow systems. While drip irrigation is highly efficient for water delivery at the plant root zone, it requires significant initial investment and maintenance, limiting its adoption in large-scale row crop farming. In contrast, surge irrigation leverages existing furrow irrigation infrastructure, making it more accessible and cost-effective for farmers. Additionally, surge irrigation provides higher application rates compared to drip systems, which can be particularly beneficial for crops that require periodic heavy irrigation (Rodriguez et al., 2004).

Compared to continuous flow furrow irrigation, surge irrigation demonstrates superior performance in terms of water savings, infiltration uniformity, and soil erosion control. Valipour (2013) showed that surge irrigation increased water productivity by up to 28%, while reducing erosion by regulating water velocity during the alternating cycles. This makes surge irrigation a practical option for regions with highly erodible soils, where continuous water flows exacerbate soil degradation.

Surge irrigation's effectiveness is influenced by soil types, climate variability, and crop water requirements. In sandy soils, water infiltrates rapidly, requiring shorter surge "on" periods to prevent deep percolation losses. In contrast, clayey soils exhibit slow infiltration rates, necessitating longer "off" periods to allow uniform water distribution. Studies conducted in Ethiopia revealed that surge irrigation significantly improved water use efficiency in vertisol soils, where conventional furrow methods failed to achieve uniform moisture distribution (Mintesinot et al., 2007). These findings underscore the importance of tailoring surge irrigation systems to local soil characteristics and climate conditions.

Furthermore, surge irrigation has shown resilience to climate variability by optimizing water application during unpredictable rainfall patterns. For example, in regions of Mexico experiencing drought stress, integrating surge irrigation with soil moisture sensors helped farmers achieve 20% higher water productivity compared to manual irrigation scheduling (Mostafazadeh-Fard et al., 2006). This demonstrates how technological integration can enhance surge irrigation's performance under changing climatic conditions.

The adoption of surge irrigation directly aligns with SDG 6 (Clean Water and Sanitation) by promoting efficient water use and reducing wastage in agriculture. As global freshwater resources continue to decline, sustainable irrigation methods are critical for meeting the food demands of a growing population. Surge irrigation also supports SDG 2 (Zero Hunger) by improving crop productivity through better water management. For example, studies in China's Hebei Province demonstrated that surge irrigation improved wheat yields by 15%, contributing to increased food production in water-scarce areas (Mahmood et al., 2023).

Despite its potential, the widespread adoption of surge irrigation faces challenges, particularly in developing countries. High initial costs, lack of technical expertise, and limited access to automated surge controllers are significant barriers. However, advancements in smart irrigation systems, powered by AI and IoT (Internet of Things), are expected to lower costs and

improve accessibility. For instance, Borhade (2018) designed an embedded surge irrigation system integrated with IoT technology, enabling remote monitoring and control of water applications. Such innovations hold the potential to make surge irrigation a scalable and sustainable solution for farmers worldwide.

Principles of Surge Irrigation

Surge irrigation operates on the principle of intermittent water flow through alternating "on" and "off" cycles, addressing inefficiencies of traditional continuous irrigation methods. The cyclic water delivery improves infiltration rates, reduces deep percolation losses, and ensures more uniform moisture distribution throughout the field (Yonts et al., 1996; Mostafazadeh-Fard et al., 2006). This process enhances water efficiency, minimizes soil erosion, and stabilizes soil moisture along furrows, making it an effective water-saving irrigation method.

Surge irrigation has been shown to save **20-40% of irrigation water** while maintaining or improving crop yields compared to continuous irrigation (Kaur et al., 2021). For instance, in maize crops, water savings reached **30%** without yield reduction, demonstrating its efficacy in real-world applications (Rodriguez et al., 2004).

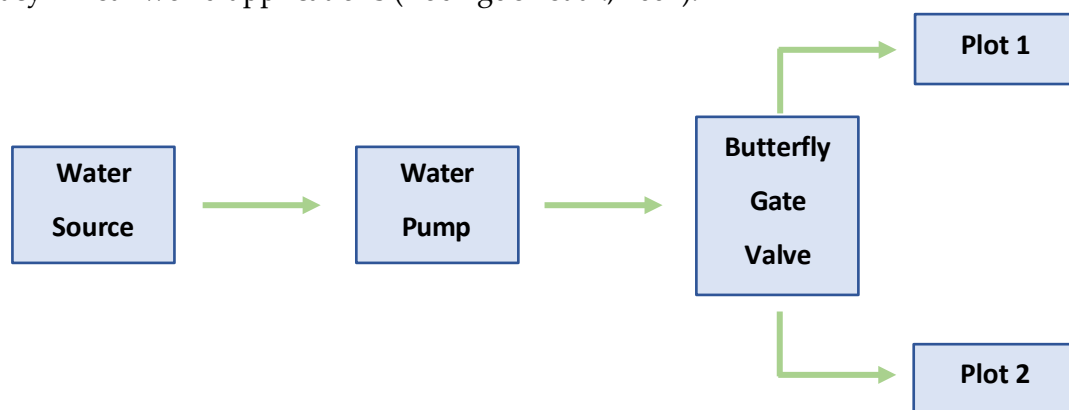
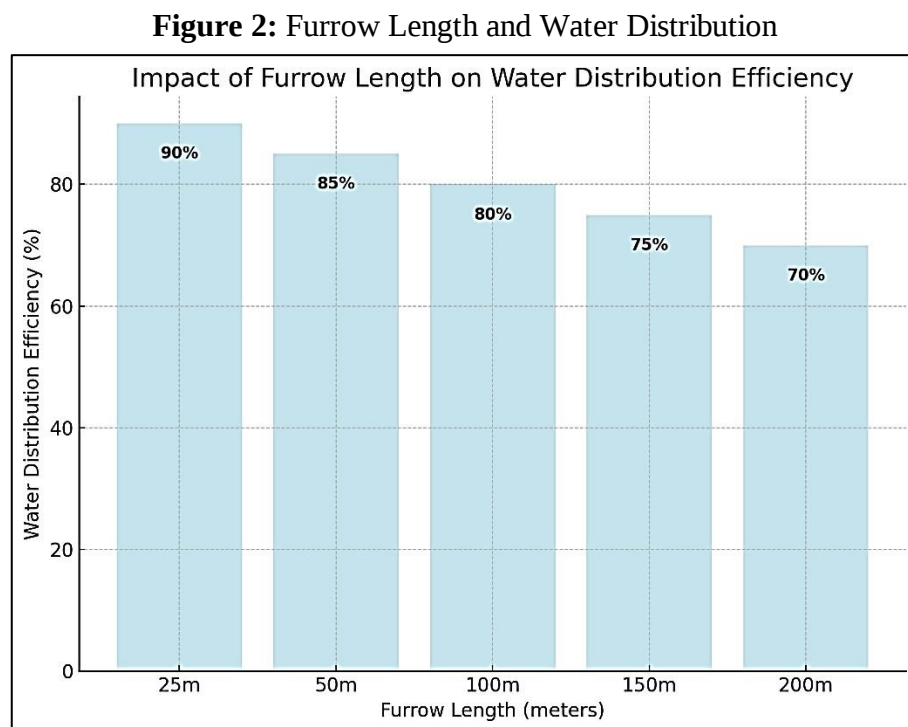


Figure 1: Surge Irrigation System Flow Diagram

The flow diagram illustrates a **surge irrigation system** where water begins at the **Water Source**—a canal, reservoir, or well—that supplies the required irrigation water. This water is then regulated by the **Water Pump**, which controls flow pressure for efficient distribution. From the pump, water passes through the **Butterfly Gate Valve**, which automates the on/off cycles to optimize water delivery. The valve directs the water flow to different **Plots** (e.g., Plot 1 and Plot 2), ensuring that it alternates and distributes water efficiently for uniform coverage across the field.

The fundamental concepts of surge irrigation are:

1. **Delivery of water:** Water is distributed intermittently into individual lengthy furrows or borders (TNAU, 2013). Typically, the length of the furrows ranges from 25 to 200 meters (TNAU, 2013).



The graph demonstrates that shorter furrows (e.g., 25m and 50m) achieve **higher water distribution efficiency** (90% and 85%, respectively), whereas longer furrows (e.g., 150m to

200m) exhibit a decline in efficiency due to increased water infiltration losses at the upstream end.

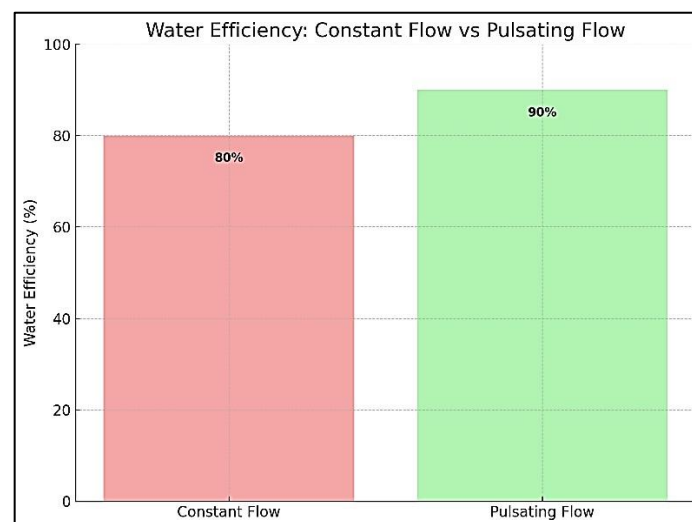
2. **On and off periods:** Alternating periods of water application and no water application characterize surge irrigation. During the "on" period, water can travel down the field by being released into the furrows (USDA, 2013). Typically, this interval is shorter than the "off" period.

Benefits:

- Prevents waterlogging at the upstream end.
- Ensures uniform infiltration along the furrow length.

3. **Constant or pulsating flow:** Implementing surge irrigation with either a constant or pulsating flow is possible. During the "on" period of constant flow surge irrigation, water is consistently discharged into the furrows (USDA, 2013). In pulsating flow surge irrigation, water is discharged in pulses or surges, consisting of brief periods of high flow followed by periods of no flow.

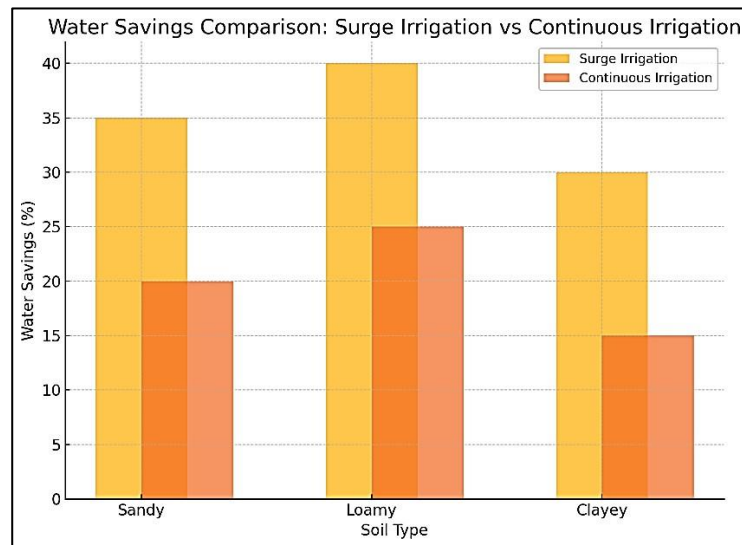
Figure 3: Constant vs. Pulsating Flow



The graph illustrates that **pulsating flow** achieves a **90% water efficiency**, compared to **80% efficiency** in constant flow systems. Pulsating flow reduces deep percolation and allows the soil to absorb water more effectively.

4. **Reduced infiltration rates:** One of the primary advantages of surge irrigation is its ability to reduce infiltration rates. By alternating the water flow, surge irrigation enables the soil to assimilate water more efficiently, thereby minimizing the quantity of water lost through deep percolation (Yonts and Eisenhauer, 2008). This can increase the efficacy of irrigation and decrease water waste.
5. **Increased uniformity:** Additionally, surge irrigation can help improve water distribution uniformity throughout the field. By modulating or alternating the flow, surge irrigation can help surmount the non-uniform infiltration and distribution issues associated with traditional continuous-flow irrigation techniques (Ware, 2022).
6. **Increased efficiency:** Surge irrigation has the potential to enhance the efficiency of surface irrigation in comparison to conventional continuous-flow methods (Fipps, 2019). By decreasing infiltration rates and increasing water distribution uniformity, surge irrigation can optimize water use and potentially reduce water and energy costs for producers (Ware, 2022).
7. **Intermittent Water Flow and Infiltration Uniformity:** The controlled cyclic water flow enables better management of **Infiltration Opportunity Time (IOT)** – the time water stays in contact with soil. In continuous irrigation, prolonged IOT causes excessive water infiltration at upstream furrow ends, leaving tail-end areas dry. Surge irrigation alternates flow cycles to prevent this imbalance, allowing water to infiltrate uniformly across the entire furrow length. For example, continuous irrigation often loses **40% of water** through deep percolation at upstream furrows, while surge irrigation reduces this to **15-20%** (Alejo & Espino, 2020). The following graph illustrates the improved water infiltration balance achieved with surge irrigation compared to continuous flow.
8. **Water Savings and Efficiency Across Soil Types:** Surge irrigation's efficiency is influenced by soil type, which determines the ideal on/off cycle durations. Sandy soils, with high infiltration rates, require shorter water application periods to prevent deep percolation, while clayey soils, which absorb water slowly, benefit from longer off cycles to allow infiltration. The following graph compares water savings (%) achieved by surge irrigation and continuous irrigation across **three major soil types** based on real-world studies (Mostafazadeh-Fard et al., 2006; Kaur et al., 2021).

Figure 4: Water Savings Comparison: Surge Irrigation vs Continuous Irrigation



9. **Infiltration Control and Soil Stabilization:** Another advantage of surge irrigation is its ability to **stabilize soil** and reduce erosion. Alternating water flows allow time for the soil to settle between cycles, minimizing sediment displacement. Rodriguez et al. (2004) reported that soil erosion was reduced by **45%** in fields irrigated with surge systems compared to continuous flow methods. Additionally, the energy requirements for surge irrigation are lower. Automated surge controllers synchronize pump operations, optimizing energy use and reducing costs, particularly in large-scale systems (Borhade, 2018).

Surge irrigation generally permits more effective and efficient water application in furrow and border irrigation systems. It aids in decreasing water loss, enhancing uniformity, and possibly enhancing irrigation efficiency.

COMPARISON WITH CONVENTIONAL METHODS

1. Water Savings Comparison

Studies have shown that surge irrigation reduces water consumption by up to **40%** compared to conventional continuous-flow irrigation systems. This is achieved through **reduced infiltration losses, optimized flow control**, and better soil absorption efficiency.

2. Crop Yield Improvement

Surge irrigation improves crop yields by optimizing water application to the root zone, ensuring uniform water distribution. Studies suggest yield improvements of up to **12-18%** in crops like wheat and maize compared to continuous-flow systems (Kaur et al., 2021; Yonts and Eisenhauer, 2008).

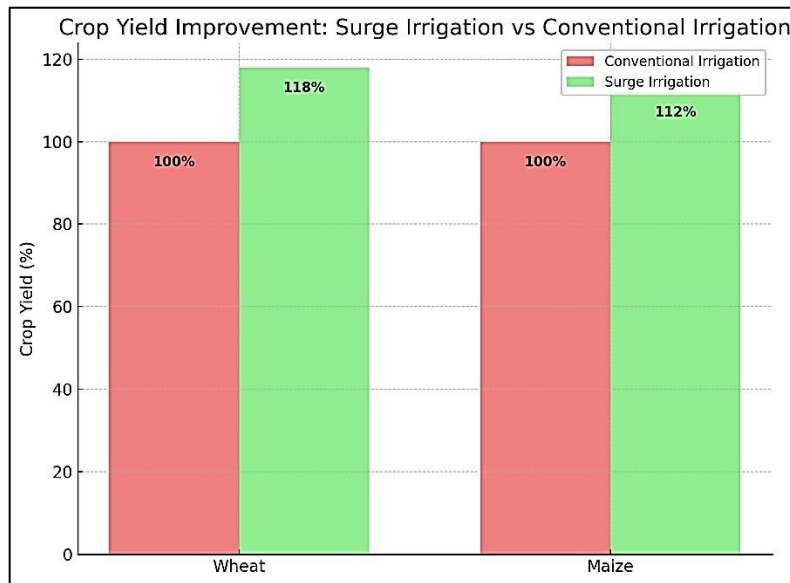


Figure 5: Crop Yield Improvement Comparison

The graph compares crop yields under conventional irrigation (baseline: 100%) and surge irrigation:

- **Wheat:** Yield increased by **18%** under surge irrigation.
- **Maize:** Yield improved by **12%**, highlighting the optimized water application to the root zone.

Surge irrigation ensures uniform moisture distribution, directly enhancing crop productivity.

3. Energy Use Efficiency

Surge irrigation optimizes energy use by reducing pump operation times. Controlled intermittent flow requires less continuous energy input compared to conventional methods.

PARAMETER	CONVENTIONAL IRRIGATION	SURGE IRRIGATION
Pump Operation Time	Continuous	Intermittent
Energy Consumption	High	Moderate to Low
Cost Efficiency	Lower	Higher

Table 1: Energy Use Comparison

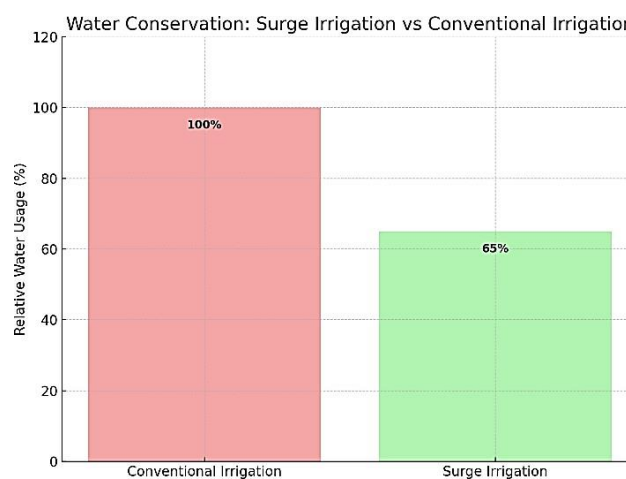
Advantages and Disadvantages of Surge Irrigation

Surge irrigation is a technique that introduces intermittent water application cycles to furrows or borders, offering unique benefits over conventional irrigation systems. However, like any method, it also has limitations. The following sections critically examine its advantages and disadvantages.

Advantages of Surge Irrigation

1. **Water Conservation:** It has been demonstrated that surge irrigation uses substantially less water than conventional irrigation methods. Surge irrigation improves water infiltration and reduces waterlogging and discharge by modulating the water flow.

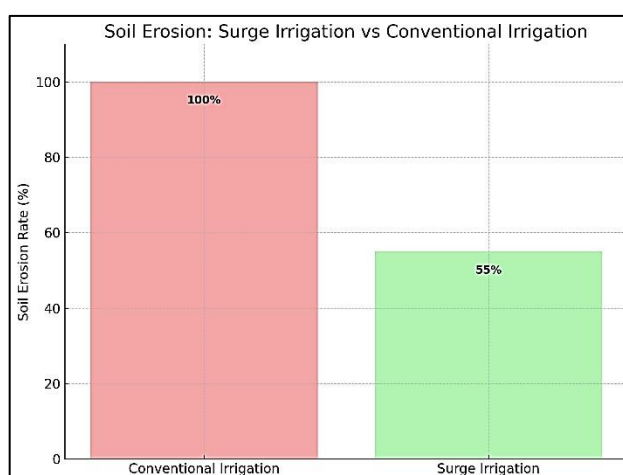
Figure 6: Water Conservation: Surge Irrigation vs Conventional Furrow Irrigation



2. **Energy Efficiency:** A surge irrigation system may be more energy-efficient than a continuous-flow system. By alternating the water flow, surge irrigation reduces the total amount of energy required for irrigation (Ware, 2022).

3. **Reduced Soil Erosion:** The oscillating action of surge irrigation reduces water velocity and allows the soil to absorb water more efficiently. This minimizes erosion and sediment loss. (Grover, 2022) found that soil erosion rates decreased by 45% in surge systems compared to continuous-flow irrigation.

Figure 7: Soil Erosion: Surge Irrigation vs Conventional Furrow Irrigation



4. **Labor Savings:** As surge irrigation requires less time and effort than continuous-flow irrigation systems, it can reduce labor costs (TNAU, 2013).

Disadvantages of Surge Irrigation

1. **Soil Type Limitations:** In extremely clayey or granular soils, there may not be a significant land and water conservation difference between surge irrigation systems (TNAU, 2013). The efficiency of surge irrigation can vary based on the type of soil.
2. **Initial Investment:** An initial investment in surge valves and other equipment may be required to implement irrigation systems. However, water and energy savings over the long term can mitigate these expenditures.

ADVANTAGES	DISADVANTAGES
Reduces water consumption by 20-40%.	Less effective in extremely clayey or sandy soils.
Improves energy efficiency (20-30%).	Requires significant initial investment in equipment.
Decreases soil erosion by up to 45%.	Not universally applicable for all soil types.
Saves labor through automation.	---

Table 2: Summary of Advantages vs Disadvantages of Surge Irrigation

The advantages of surge irrigation include water conservation, energy efficiency, and reduced soil erosion. However, it may not be appropriate for all soil varieties, and there may be initial investment costs. Surge irrigation offers substantial advantages, including **water conservation**, **energy efficiency**, **reduced soil erosion**, and **labor savings**. However, its effectiveness depends on soil type, and initial setup costs can be a limiting factor. The overall

benefits make surge irrigation a valuable tool for improving agricultural sustainability and efficiency.

Components of a Surge Irrigation System

The components of a surge irrigation system typically include (TNAU, 2013; USDA, 2013; Yonts and Eisenhauer, 2008):

1. **Surge valve:** a critical device that regulates the flow of water into irrigation furrows by delivering water in intermittent surges. It allows water to flow in **controlled on- and-off cycles**, which improve water infiltration rates and prevent excessive saturation of soil. The surge valve ensures uniform water distribution across the field by modulating the flow duration and pressure, addressing the issue of waterlogging at upstream ends while enabling sufficient infiltration at downstream areas. Modern surge valves are often equipped with **programmable automation features**, making them suitable for a wide range of field conditions and irrigation needs.
2. **Surge controller:** a device responsible for managing the timing and duration of water surges. It determines the precise intervals for the "on" and "off" cycles of water delivery, optimizing infiltration and reducing water losses. Advanced controllers can integrate with soil moisture sensors and other technologies to adapt irrigation schedules based on real-time field data. This feature makes surge irrigation highly efficient, as it tailors water delivery to specific soil conditions and crop requirements. By automating the regulation process, the surge controller minimizes human intervention while ensuring accurate water application.
3. **Water supply:** forms the foundation of the surge irrigation system, providing water for distribution across the field. It may originate from a **canal, reservoir, well, or other surface water sources**. The water supply must maintain sufficient **pressure and flow rates** to ensure consistent delivery throughout the system. Clean water is critical for the proper functioning of valves and controllers, as sediments or impurities can clog the system components. The availability and reliability of the water supply directly impact the performance and efficiency of the irrigation system, particularly in areas prone to water scarcity.
4. **Distribution system:** consists of an interconnected network of **pipes, gates, and channels** that convey water from the supply source to the irrigation furrows. Pipes made from materials like **PVC or HDPE** ensure minimal leakage and smooth water transport over long distances. Gates and channels serve as regulators, allowing water to be directed to specific furrows based on irrigation requirements. In surge

irrigation, the distribution system is carefully designed to accommodate the cyclic water flow, ensuring that surges reach their intended location without pressure loss or runoff. Proper maintenance of the distribution system is essential to ensure its long-term performance and efficiency.

5. **Irrigation furrows:** are long, narrow trenches created in the soil to guide water flow directly to crop root zones. Their dimensions—length, width, and slope—are customized based on soil texture, field topography, and crop type to maximize water infiltration. In surge irrigation, controlled pulses of water ensure that furrows are evenly wetted along their entire length. This prevents water stagnation at upstream ends while improving moisture distribution downstream. Well-maintained furrows enhance the effectiveness of surge irrigation, allowing for efficient water use and better crop growth.
6. **Soil moisture sensors:** are devices used to monitor the moisture content in the soil, providing accurate data to farmers for optimizing irrigation schedules. By assessing the soil's water-holding capacity, these sensors ensure that water is applied only when necessary, reducing over-irrigation and water waste. Integrating soil moisture sensors with surge controllers allows for precision irrigation, where water delivery is adjusted dynamically based on soil conditions. This technology enhances water-use efficiency, supports plant health, and minimizes energy consumption, particularly in resource-limited areas.
7. **Pumping system:** is responsible for delivering water from the supply source to the distribution system. Pumps ensure consistent flow rates and maintain the required pressure to sustain water delivery during surge cycles. In surge irrigation, the pump's operation is intermittent, reducing energy use compared to continuous-flow systems. Pumps can be powered by **electric motors, diesel engines, or renewable energy sources** like solar power, depending on availability and cost considerations. Proper pump selection and maintenance are vital to ensuring the system's reliability, efficiency, and longevity.

These components work together in a synchronized manner to deliver water intermittently to the crops. The use of surge irrigation enhances **water-use efficiency**, reduces energy consumption, minimizes soil erosion, and improves crop yields by ensuring uniform water distribution across the field (Grover, 2022).

Surge Irrigation vs. Conventional Method

In terms of water delivery and water administration, surge irrigation and conventional irrigation techniques, such as continuous flow furrow irrigation, are distinct. Compared to conventional irrigation methods, the application efficacy of surge irrigation is typically superior. Application efficacy is the proportion of administered water that reaches the root zone of plants and is available for crop absorption.

Kaur, Kaushal, and Shelke (2021) conducted a study comparing the water productivity and savings of six crops under surge irrigation with traditional methods for crops cultivated in various environmental conditions and geographic locations. The conclusion is that surge flow irrigation is superior to continuous flow irrigation regarding water conservation and yield, thereby increasing water productivity. In the case of wheat crops, surge irrigation saved and reduced irrigation water by 27, 33.4, and 37.4% and increased productivity by 15.1, 17.7, and 12.7% under slopes of 0, 0.1, and 0.2%, respectively, when compared to continuous flow irrigation with the same discharge. Its maximum water use efficiency values for surge flow irrigation on slopes of 0, 0.1, and 0.2% were 1.39, 1.56, and 1.59 kg/m³, respectively.

Slope (%)	Water Saved (%)	Productivity Increase (%)	Water Use Efficiency (WUE) (kg/m ³)
0	27	15.1	1.39
0.1	33.4	17.7	1.56
0.2	37.4	12.7	1.59

Table 3: Water Savings and Productivity for Wheat Crops

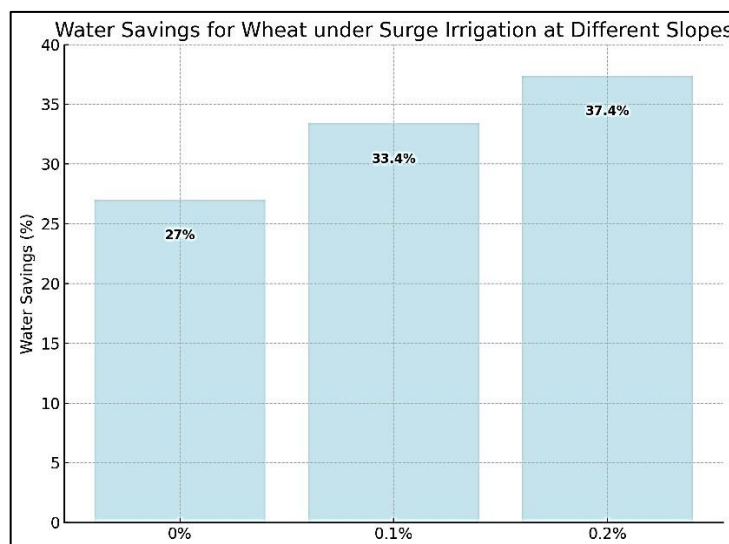


Figure 8: Water Savings for Wheat under Surge Irrigation at Different Slopes

Surge irrigation saved between **27% and 37.4%** of irrigation water as the slope increased from **0% to 0.2%**. The results highlight the efficiency of surge irrigation in optimizing water delivery while minimizing losses.

The surge irrigation system for maize produced the highest WUE (1.63 kg/m³) with a 40 m furrow length under a 12.24 l/min inflow rate. A continuous irrigation system produced the lowest WUE (1.05 kg/m³) with a 20 m furrow length under a 44.4 l/min inflow rate.

Irrigation Type	Inflow Rate (l/min)	Furrow Length (m)	Water Use Efficiency (kg/m ³)
Surge Irrigation	12.24	40	1.63
Continuous Irrigation	44.4	20	1.05

Table 4: Water Use Efficiency in Maize

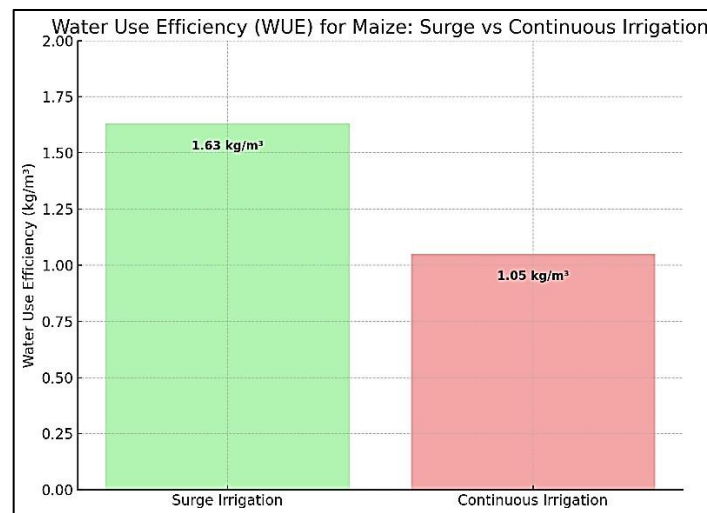


Figure 8: Water Savings for Wheat under Surge Irrigation at Different Slopes

The graph highlights that surge irrigation significantly improves **water use efficiency (WUE)** for maize crops, achieving **1.63 kg/m³** compared to **1.05 kg/m³** in continuous irrigation systems. The controlled delivery of water in surges reduces infiltration losses, maximizing crop yield per unit of water.

Valipour (2013), on the other hand, utilized various types of ingress regimes, such as continuous flow, cutback, fixed surge, and variable surge, to increase irrigation efficacy in border irrigation. Cutback and surge irrigation methods improved irrigation efficiency by 11.66% and 28.37%, according to simulation results obtained using the SIRMOD software.

IRRIGATIONMETHOD	EFFICIENCYIMPROVEMENT(%)
Continuous Flow	Baseline (0%)
Cutback	11.66%
Surge Irrigation	28.37%

Table 5: Irrigation Efficiency Improvements

In their study, Rodriguez et al. (2004) compared the hydraulic behavior of different water management strategies of furrow irrigation for the cultivation of black tobacco in

Ferralsol soil using a simulation model of surface irrigation. They found that surge irrigation increased water application efficiency. The intermittent application of water significantly diminished the soil's infiltration capacity. Similarly, the effect of soil water content and furrow- wet perimeter on infiltration parameters was confirmed. Compared to continuous irrigation, the surge flow furrow irrigation with variable time cycles increased application efficiency by more than sixfold and decreased water volume by more than 80 percent.

Mintesinot et al. (2007) examined the potential for enhancing conventional irrigation techniques by incorporating surge irrigation and scheduling to determine irrigation frequency. Using maize as an indicator crop, traditional irrigation management (without scheduling) and surge/intermittent irrigation (with scheduling) were compared over two irrigation seasons. Yield, water output, and fiscal yield were measured. Their findings demonstrated that surge irrigation with scheduling produced a crop yield 2.3 times that of conventional irrigation. Surge management increased water productivity and income by 2.7 and 2.8 times compared to conventional management.

PARAMETER	CONVENTIONALIRRIGATION	SURGEIRRIGATION
Crop Yield	Baseline	2.3 times higher
Water Productivity	Baseline	2.7 times higher
Income	Baseline	2.8 times higher

Table 6: Comparative Crop Performance

Surge irrigation demonstrates significant advantages over conventional continuous-flow methods in terms of **water savings, crop productivity, and irrigation efficiency**.

- Water savings for wheat crops range from **27% to 37.4%**, depending on field slopes.
- Water use efficiency for maize under surge irrigation is **1.63 kg/m³**, compared to **1.05 kg/m³** in conventional systems.
- Irrigation efficiency in border irrigation improves by **28.37%** under surge irrigation.

- Maize yields increase **2.3 times**, with water productivity and income gains of **2.7 and 2.8 times**, respectively.

These findings underline the potential of surge irrigation to enhance water management practices, improve sustainability, and maximize agricultural productivity.

Overall, surge irrigation has the potential to considerably increase application efficacy compared to conventional methods. By more precisely delivering water to the root zone of plants, surge irrigation reduces water loss and maximizes crop water absorption. This enhanced efficacy can result in water savings, improved crop performance, and more sustainable water management practices.

CHALLENGES WITH SURGE IRRIGATION

While surge irrigation offers several advantages in terms of water distribution and efficacy, it is not without its drawbacks. The technology of surge irrigation is still relatively new and may require specialized infrastructure and apparatus (Yonts and Eisenhauer, 2008). Surge irrigation requires additional infrastructure, such as surge controllers and monitoring systems, to be implemented. Availability, cost, and maintenance of the necessary components, such as overload valves and controllers, can become problematic. Initial investment and ongoing maintenance costs can be higher than traditional furrow irrigation methods, which may deter some farmers, particularly those with limited resources.

Surge flow may not always reduce the advance time of water down the furrow (Yonts, 2001; Yonts and Eisenhauer, 2008). This indicates that the intended benefits of surge irrigation, such as enhanced water distribution and decreased water loss, may not always be realized. Moreover, in extremely clayey or powdery soils, surge irrigation may not demonstrate significant differences in land and water savings (Yonts and Eisenhauer, 2008). The efficacy of surge irrigation can vary based on the type of soil and its capacity to absorb and retain water. Optimizing the benefits of surge irrigation requires proper management and expertise. This includes determining the appropriate surge on time and the extent of the furrow stream (TNAU, 2013). Farmers must comprehend the principles and techniques of surge irrigation in order to implement and manage the system effectively. Designing, installing, and operating surge irrigation systems can be more difficult than conventional irrigation methods. Inaccurate or improper timing of surge cycles can result in irregular water distribution, potentially resulting in over- or under-watering of crops.

During the active phases of surge irrigation, the higher flow rates can increase soil erosion and sediment transport within the furrows. This erosion may result in soil degradation and diminished soil fertility over time. During periods of stagnant water, surge irrigation can promote the growth of weeds, particularly during the off-season. Weeds can reduce crop yields by competing with crops for water and nutrients. In addition, producers must acclimate to a new system to transition from traditional irrigation methods to surge irrigation. A learning curve may exist, and some producers may hesitate to implement this unfamiliar technique.

Despite these obstacles, it has been demonstrated that surge irrigation has

prospective benefits in terms of water conservation and increased crop yields (USDA, 2013). Before deciding to implement surge irrigation, producers must thoroughly evaluate their particular conditions and needs. Planning, administration, and monitoring can assist in overcoming these obstacles and optimizing the benefits of surge irrigation.

CHALLENGE	DETAILS
High Initial Investment	Surge systems require surge controllers, valves, and monitoring systems.
Maintenance Costs	Regular upkeep of valves and controllers adds to operational expenses.
Soil Type Limitations	Ineffective in clayey soils (low infiltration) or sandy soils (high loss).
Expertise and Management	Requires technical knowledge to optimize cycle timing and water flow.
Soil Erosion	High flow rates increase soil erosion, leading to reduced soil fertility.
Weed Growth	Stagnant water phases promote weed development, affecting crop yields.

Table 7: Key Challenges with Surge Irrigation

DEVELOPMENT OF SURGE IRRIGATION

Surge irrigation represents a significant technological advancement in furrow irrigation systems. Its evolution has been driven by the increasing need for **efficient water management, labor reduction, and sustainable agricultural practices**. While traditional furrow irrigation systems have been widely used, their limitations—such as deep percolation losses, uneven water distribution, and excessive water consumption—spurred the development of more sophisticated techniques like surge irrigation. This method employs **intermittent water delivery**, optimizing water infiltration and minimizing wastage. Over the years, numerous technological and automated systems have been developed to enhance the performance and practicality of surge irrigation, making it a viable solution for modern agriculture.

Early Developments and Automation

The earliest developments in surge irrigation sought to automate water delivery while addressing the inefficiencies of manual systems. Automation in irrigation systems has been a key focus since the mid-1980s, driven by the demand for labor savings and precision water management.

Testezlaf et al. (1986) pioneered the integration of automation into surge irrigation systems by introducing a **rotating gate system**. Their study explored the application of the surge flow technique to open-channel furrow irrigation systems. The rotating gate was

automated to control water delivery intervals, enabling the flow to alternate between surges. The results showed that the **automated system reduced labor requirements**, which was a significant improvement over traditional systems that required manual monitoring and adjustments. Additionally, the system enhanced overall irrigation performance by delivering consistent and precise water amounts, thereby improving infiltration efficiency. This study demonstrated the potential for automation to make surge irrigation more **reliable** and **cost-effective** in labor-intensive agricultural settings.

Advancements in Surge Valve Design

Further developments focused on improving the functionality and cost-efficiency of **surge valves**—critical components that regulate the timing and duration of water surges.

Mostafazadeh-Fard, Osroosh, and Eslamian (2006) designed and tested an **automatic surge valve** that could adapt to varying soil and field conditions. The valve was portable, wireless, and powered by a **rechargeable battery** that could be recharged using a **solar panel** for extended use. This innovation was particularly significant for resource-limited agricultural areas where access to reliable power sources was a challenge. The study found that surge flow significantly reduced water advance time compared to continuous flow systems, allowing water to reach the furrow's tail end **more quickly and uniformly**. Additionally, for the same volume of water applied, surge irrigation **improved water infiltration efficiency** while reducing water wastage. The incorporation of **solar-powered technology** into surge irrigation systems marked a critical step toward energy-efficient and environmentally sustainable agricultural practices.

In another advancement, **Mathew and Senthilvel (2007)** field-tested an **automatic surge irrigation system** equipped with a **time switch and electromagnetic valve**. Their system was evaluated on **120 cm paired-row furrows**, and its performance was compared to traditional continuous flow systems. The results were promising:

- The **advance time** for water to reach the furrow's tail end was reduced by **48%** under surge irrigation.
- Surge irrigation achieved **uniform soil moisture distribution** more effectively than continuous flow irrigation, particularly in longer furrows. However, the study identified practical limitations. While surge irrigation improved advance time, its performance diminished in furrows longer than **120 meters**, where the proportion of advance time relative to total irrigation duration increased significantly (59%). This highlighted the need for further optimization to expand the applicability of surge systems to larger fields.

Integration of Smart Technologies and IoT

The development of surge irrigation has progressed further with the integration of **smart technologies**, such as microcontrollers, sensors, and Internet of Things (IoT) systems. These innovations have enhanced the precision, efficiency, and monitoring capabilities of surge irrigation systems.

Borhade (2018) introduced a **microcontroller-based surge controller** that integrated real-time monitoring and data communication using IoT technology. This system, powered by an **ARM Cortex M3 microcontroller**, enabled multitasking through a real-time operating system (FreeRTOS). The IoT functionality allowed the system to transmit irrigation data to a remote station using **GPRS-based communication**, eliminating the need for physical monitoring of irrigation events in the field. Borhade's innovation addressed one of the significant challenges in surge irrigation—labor dependency—by enabling virtual monitoring and automation. The integration of **AES encryption** ensured secure data communication, which is crucial for large-scale commercial farming operations. This “smart” surge controller showcased the potential for **digital agriculture** to transform irrigation practices by reducing labor costs, improving water efficiency, and providing real-time decision-making support.

Field Testing and Efficiency of Surge Gates

Surge gates are another essential component in the development of surge irrigation systems. They automate the **on-off action** of water delivery, enabling precise control of water flow rates and surges.

Mahmood et al. (2023) developed and tested a **basic automatic surge gate** to evaluate its performance in producing on-off surges. The system incorporated a **reservoir** to capture inflows and regulate water outflows through a surge gate positioned on the suction side. The study demonstrated the feasibility of automating surge flow even with **minimal inflow rates** (as low as **134 l/s**). The surge gate produced sizable water outflows, which validated its effectiveness in **reducing water advance time** and improving infiltration uniformity. This development is particularly beneficial in regions with limited water availability, as it enables controlled water delivery while minimizing wastage.

Efficiency Gains and Limitations

The advancements in surge irrigation systems have demonstrated significant improvements in **water efficiency** and **irrigation performance**. However, the technology also faces limitations that must be addressed to ensure its widespread adoption.

1. Improved Water Use Efficiency:

Studies have consistently shown that surge irrigation improves **water use efficiency (WUE)** by reducing deep percolation losses and ensuring uniform water distribution. For example:

- Mathew and Senthilvel (2007) observed that surge irrigation reduced water advance time by **48%**, allowing for faster and more uniform infiltration.
- Mostafazadeh-Fard et al. (2006) reported that surge irrigation improved infiltration efficiency while maintaining energy-efficient water delivery.

2. Field Size Limitations:

While surge irrigation performs well in smaller and medium-sized fields, its

effectiveness diminishes in longer furrows. Mathew and Senthilvel (2007) noted that the proportion of advance time relative to net irrigation time increased to **59%** in furrows longer than **120 meters**. This limits its applicability to large-scale fields unless further optimization is achieved.

3. Dependence on Soil Properties:

The success of surge irrigation depends heavily on soil properties. In highly clayey soils, infiltration rates are naturally low, reducing the effectiveness of surge flow. Conversely, in sandy soils, water may infiltrate too quickly, negating the benefits of intermittent surges. This variability highlights the need for site-specific system design and management.

4. Technical Knowledge and Adoption Barriers:

The implementation of advanced surge irrigation systems requires specialized technical knowledge. Farmers must understand the principles of surge flow, system design, and management to optimize performance. Additionally, the initial cost of equipment— such as surge valves, controllers, and sensors—can deter adoption, particularly in resource-limited regions.

Future Trends and Research Directions

The continued development of surge irrigation is expected to focus on **enhancing automation, improving system efficiency, and reducing costs**. Emerging technologies, such as **artificial intelligence (AI)** and **machine learning**, hold promise for optimizing irrigation schedules based on real-time field data. Additionally, the integration of **solar-powered systems** can address energy constraints and make surge irrigation more accessible to remote and underserved areas.

Future research should prioritize the following areas:

1. **Field Optimization:** Developing systems capable of efficiently irrigating longer furrows and larger fields.

2. **Soil-Specific Solutions:** Designing adaptable surge systems for various soil types, including clayey and sandy soils.
3. **Cost Reduction:** Innovating low-cost surge valves, controllers, and monitoring systems to make surge irrigation affordable for smallholder farmers.
4. **Sustainability:** Integrating renewable energy sources and IoT-based smart systems to reduce environmental impact and energy dependency.

The development of surge irrigation has marked a significant step forward in furrow irrigation technology. From its early automation experiments in the 1980s to modern IoT-enabled “smart” systems, surge irrigation has demonstrated its potential to enhance water use efficiency, reduce labor dependency, and promote sustainable agricultural practices. Innovations such as **solar-powered valves**, **microcontroller-based controllers**, and **automatic surge gates** have further expanded the practicality and precision of surge systems. However, challenges related to **field size limitations**, **soil variability**, and **technical adoption** remain critical areas for improvement. Continued research, innovation, and farmer education will play a crucial role in overcoming these obstacles and unlocking the full potential of surge irrigation for modern agriculture.

Conclusion

Surge irrigation stands as one of the most innovative advancements in **agricultural water management** over the past few decades. This method has emerged in response to the persistent challenges of traditional furrow irrigation, particularly inefficiencies such as **irregular water distribution**, **deep percolation losses**, and **runoff-induced water waste**. By introducing **cyclic water flow**, surge irrigation transforms how water is delivered to crops, ensuring more controlled, uniform, and efficient water application while mitigating some of the environmental issues associated with conventional irrigation methods.

The primary advantage of surge irrigation lies in its ability to optimize **application efficiency**. Unlike continuous-flow systems where water accumulates excessively at upstream ends while downstream furrows remain dry, surge irrigation uses alternating **on-off cycles** to allow water to advance steadily. This enhances water infiltration while preventing waterlogging and runoff, leading to improved **water use efficiency (WUE)**. Studies have demonstrated that surge irrigation can reduce water usage by **20-40%** while maintaining or improving crop yields, particularly for water-intensive crops like maize and wheat (Mostafazadeh-Fard et al., 2006; Kaur et al., 2021). This significant reduction in water consumption makes surge irrigation particularly valuable in arid and semi-arid regions where water resources are scarce and under increasing pressure.

Enhanced Crop Performance and Yield

Surge irrigation has demonstrated a consistent ability to improve **crop performance** and **yield outcomes**. By ensuring water reaches the **root zones** of crops uniformly, it eliminates the irregularities in moisture distribution that are common in continuous irrigation. This uniform water availability reduces plant stress and promotes more consistent crop growth. For instance, in wheat cultivation, surge irrigation has been shown to increase crop yields by **15- 18%** compared to continuous flow systems, depending on field slope and soil conditions (Kaur et al., 2021). Similarly, in maize cultivation, surge irrigation achieved water use efficiencies of up to **1.63 kg/m³**, compared to just **1.05 kg/m³** under traditional methods. These results

underscore the potential for surge irrigation to support increased agricultural productivity while using water more judiciously.

Furthermore, surge irrigation minimizes the occurrence of **water-related crop diseases** that are exacerbated by excessive water stagnation and poor drainage under continuous irrigation. By reducing over-saturation and waterlogging, surge irrigation creates healthier soil conditions, which contribute to improved plant growth and resilience.

Water Conservation and Environmental Sustainability

Water scarcity has become a critical challenge globally, particularly in regions where agricultural water demand far exceeds supply. Surge irrigation offers a sustainable solution by conserving water and minimizing wastage. The cyclic nature of surge irrigation allows water to infiltrate the soil **incrementally**, reducing deep percolation losses. Research has shown that water savings of **20-40%** can be achieved without compromising crop yield (Yonts and Eisenhauer, 2008; Rodriguez et al., 2004). Such efficiency gains make surge irrigation highly relevant in the context of **climate change**, where unpredictable rainfall patterns and prolonged droughts threaten agricultural productivity.

Another significant environmental benefit of surge irrigation is its role in **reducing soil erosion**. Traditional irrigation systems often produce high water velocities, leading to the displacement of topsoil and sediment transport. Surge irrigation mitigates this issue by controlling flow rates and reducing water velocity during delivery, thereby preserving soil structure and fertility. Studies have reported that surge irrigation can reduce soil erosion by **45%** compared to continuous-flow systems (Grover, 2022). This reduction is critical for maintaining long-term soil health and ensuring sustainable agricultural practices.

By conserving water, minimizing erosion, and enhancing crop yields, surge irrigation aligns with global efforts to achieve the **Sustainable Development Goals (SDGs)**, particularly **SDG 6** (Clean Water and Sanitation) and **SDG 2** (Zero Hunger). Implementing surge irrigation on a broader scale can help mitigate the adverse effects of water scarcity while promoting food security.

Challenges and Barriers to Adoption

While the benefits of surge irrigation are well-documented, its implementation is not without challenges. The primary barrier is the **high initial investment** required for infrastructure, including surge valves, controllers, and monitoring systems. Compared to traditional furrow irrigation, surge systems require specialized equipment that may be cost-prohibitive for smallholder farmers, particularly in developing regions. Maintenance costs for surge controllers and valves can also add to the financial burden, deterring widespread adoption.

Another challenge is the **technical expertise** needed to design, operate, and manage surge irrigation systems effectively. Achieving optimal results with surge irrigation requires precise coordination of surge cycles, furrow lengths, and inflow rates. Inadequate knowledge or improper system management can lead to irregular water distribution, negating the benefits of surge irrigation. Training farmers and agricultural technicians to implement surge irrigation correctly is therefore crucial for its success.

The **variability of soil types** also poses a significant limitation. In **highly clayey soils**, the infiltration rate is naturally slow, which can reduce the effectiveness of surge irrigation. Conversely, in **sandy soils**, water may infiltrate too quickly, resulting in uneven moisture distribution and reduced water savings. These soil-specific challenges highlight the need for tailored solutions and site-specific designs to optimize surge irrigation performance.

Moreover, surge irrigation systems must contend with issues such as **soil erosion during active phases** and **weed growth** during stagnant phases. High flow rates in surge irrigation can increase soil erosion if not carefully managed, while stagnant water during the "off" periods can promote weed growth, reducing crop yields. Addressing these challenges requires ongoing research and innovation to refine surge irrigation systems and mitigate their limitations.

Technological Advancements and Automation

The integration of **automation** and **smart technologies** has significantly advanced surge irrigation, making it more efficient, user-friendly, and adaptable to diverse field conditions. Early developments, such as the automated surge gates introduced by **Testezlaf et al. (1986)**, laid the groundwork for modern surge irrigation systems. These early systems demonstrated the feasibility of reducing labor requirements while enhancing water delivery precision.

In recent years, the development of **microcontroller-based systems** and **Internet of Things (IoT)** technology has revolutionized surge irrigation. For example, **Borhade (2018)**

developed a **smart surge controller** that uses IoT-enabled monitoring to provide real-time data on irrigation events. This innovation eliminates the need for farmers to be physically present in the field, allowing for remote management and monitoring of irrigation schedules. Such advancements have made surge irrigation more accessible and efficient, particularly in commercial agriculture where precision and scalability are essential. Solar-powered surge valves, as designed by **Mostafazadeh-Fard et al. (2006)**, have also addressed the energy challenges associated with irrigation systems. By utilizing **renewable energy**, these systems offer a sustainable solution for regions with limited access to electricity. The combination of **automation**, **renewable energy**, and **smart monitoring** has made surge irrigation a more viable option for modern agriculture.

Future Prospects for Surge Irrigation

Looking forward, surge irrigation holds immense promise for addressing the global challenges of **water scarcity**, **food security**, and **sustainable agriculture**. Emerging technologies, such as **artificial intelligence (AI)**, **machine learning**, and **remote sensing**, offer new opportunities to further optimize surge irrigation systems. AI-driven models can analyze real-time field data to predict water requirements, adjust surge cycles dynamically, and maximize irrigation efficiency.

Research and development should focus on addressing the following areas to expand the adoption and effectiveness of surge irrigation:

1. **Cost Reduction:** Developing low-cost surge valves, controllers, and monitoring devices to make surge irrigation more affordable for small-scale farmers.
2. **Soil-Specific Solutions:** Designing adaptable systems that account for varying soil infiltration rates, ensuring consistent performance across diverse field conditions.
3. **Scalability:** Refining surge irrigation systems to efficiently irrigate larger fields and longer furrows.
4. **Farmer Training and Education:** Providing comprehensive training programs to equip farmers with the knowledge and skills needed to implement and manage surge irrigation systems effectively.

In conclusion, surge irrigation represents a transformative approach to agricultural water management, offering substantial benefits in terms of **water conservation**, **crop performance**, and **environmental sustainability**. By addressing the inefficiencies of conventional irrigation methods, surge irrigation has the potential to revolutionize agricultural practices, particularly in regions facing water scarcity and climate challenges. The integration of advanced technologies, such as **automation**, **IoT**, and **renewable energy**, has further enhanced the practicality and efficiency of surge irrigation systems.

However, widespread adoption of surge irrigation requires overcoming barriers such as **high initial costs**, **technical knowledge gaps**, and **soil-specific limitations**. Collaborative efforts among researchers, policymakers, and agricultural stakeholders are essential to

promote surge irrigation as a sustainable and scalable solution. Investments in **research, training, and infrastructure development** will play a crucial role in optimizing surge irrigation systems and making them accessible to farmers worldwide.

As the global demand for food continues to rise, the adoption of water-efficient practices like surge irrigation will be critical for ensuring **food security, water resource sustainability, and climate resilience**. Surge irrigation not only addresses the immediate needs of water conservation but also paves the way for a more **sustainable, productive, and resilient agricultural future**.

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Bionote

Mr. Gabriel Angelo L. Rubia, CSPE, M.Sc. (cand), is a multidisciplinary professional with a robust background in engineering and research. He holds a Bachelor's degree in Electronics and Communications Engineering and previously served as a student research assistant under Prof. Rodrigo C. Muñoz Jr., former Research and Development Office Director at Bataan Peninsula State University (BPSU). Mr. Rubia is a staff member at the Environmental Sustainability Office (ENSO) at Bataan Peninsula State University (BPSU) where he is involved in administrative operations and mentors engineering students as a thesis technical adviser.

Mohamad Safaat, S.Pd. is a lecturer at Universitas Bina Mandiri Gorontalo and the Journal Manager for the Journal Proceedings of the International Interdisciplinary Conference on Sustainable Development Goals (IICSDGs), the Journal of Education and Culture. He works on managing scientific publications, promoting an interdisciplinary approach, and disseminating research in educational and cultural studies.